



Introduction

- Why is NASA involved with the Ørsted mission?
 - Danish magnetic field mapper
 - NASA/GSFS Magsat last and only precision mapper of Earth's magnetic field
 - A NASA refly of a Magsat-like mapper estimated at \$500M
 - Complex optical transfer system of Magsat replaced by non-magnetic star tracker head

NASA interested in remapping the field, therefore, backing Ørsted with \$10M of support

Introduction (cont.)

- What is NASA involvement?
 - Launch support services on AF Delta II
 - » Late 1997, Vandenberg AFB, CA
 - » ARGOS main payload
 - » South African Sunsat other piggyback payload
 - JPL supplied Turbo Rouge GPS receiver
 - Geophysics and data analysis support
 - JPL review, testing and evaluation of star tracker design and performance at JPL, JPL/TMO and Mauna Kea, Hawaii
 - Stellar/magnetic intercalibration of Ørsted payload
 - » JPL Table Mountain Observatory (TMO)
 - » CSC/ASC intercalibration 23, 24 October, 1996
 - » 2 arcsec in 2 days vs. 10+ arcsec in 33 days in Denmark
 - » Unprecedented high accuracy realized
 - Determine if the 127g camera head realizes 5 arcsec accuracy



First Generation Solid State Star Trackers

- Tracks a small number (2-6) of "brighter" stars
- Outputs star centroids in CCD coordinates
- Not autonomous, requires substantial external processing, star cataloging
- Ball 600 series, HDOS 1003, SIRA ROSAT typical commercial implementations
- High mass, high power consumption, expensive
- Suffers from large position jumps as one star enters or leaves FOV

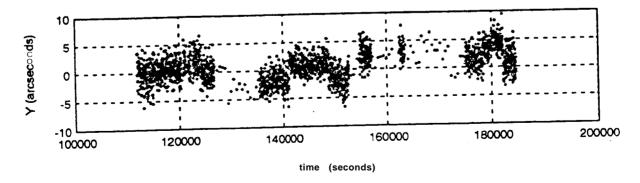
Second Generation Solid State Star Trackers

- Tracks a large number (20 to 200) of "dimmer" stars per frame, averages star positions for improved accuracy
- Quaternion Output referenced to celestial coordinates
- Fully Autonomous
- Internal star catalogs and processing
- Analog like, robust behavior—loss of stars degrades accuracy by square root of number lost
- Single star effects greatly reduced by averaging of star positions
- Technical University of Denmark (DTU) and LMMS (Palo Alto) designs most advanced

Position Residual Jumps in a First Generation Unit

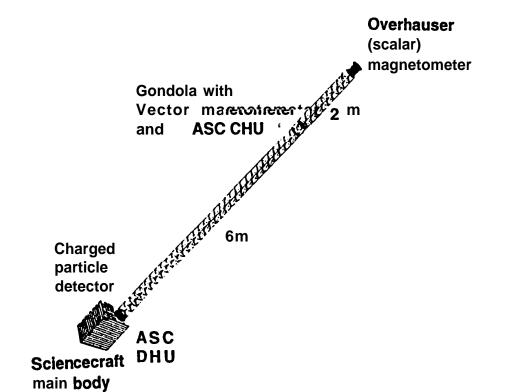
- Stars enter and leave a moving field-of-view
- . Calibration residuals of each star different
- Three to five stars typically tracked in first generation units
- Gain or loss of one star causes measured output attitude jumps up to 15 arcsec
- Single star position jumps reduced to less than 1 arcsec in the ASC

Typical Measured Attitude Jumps in NEAR Tracker*





The Ørsted Satellite



Parameter	Value
Mass:	61.4 kg
Width:	45.0 cm
Depth:	34.0 cm
Height:	68.0 cm
Boor ⁿ	8.0 m
Power:	Solar panel/batteries, avg. 54/22 W
Stabilization:	Gravitational/magnetic- torquers
Orbit:	Polar, 450 x 850 km

CHENTALANTIA

The Advanced Stellar Compass_(ASC)____

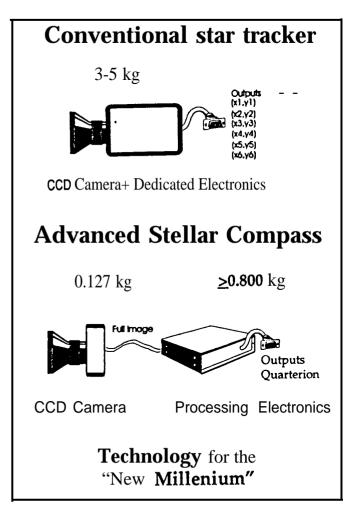
- Developed by Technical University of Denmark for the Ørsted geomagnetic satellite
- Ørsted mission supported by NASA
 - GSFC Magsat follow-on
 - 61.4 kg microsatellite
 - Polar orbit
 - A piggyback launch, late 1997, Delta II, Vandenberg AFB
- Two units: camera head and processor separation permits very low mass, low power head with high accuracy ball kinematic mount
- . Low cost COTS components
 - Radiation resistant and tested
 - Sony camcorder CCD chip set
 - 486 processor
- . Cost Goals <\$75k head, <\$75k processor for Astrid II version
- 0.5 kg, 0.5 W camera head exceeds performance of 9.0 kg, 8 W Cassini SRU

The Advanced Stellar Compass (ASC) (cont.)

- Baselined for X-2000 missions
 - Pluto Express
 - Europa
 - Solar Grazer
- Applicable to wide range of missions
 - Multiple Mars launches
 - Small, low cost spacecraft
 - Target tracking
- Single axis, 1-sigma accuracy of 5 arcsec including mechanical mounting uncertainties (vs. values of 20 to 50 arcsec for most commercial trackers)
- 2,000 and 10,000 star internal catalogs enable autonomy

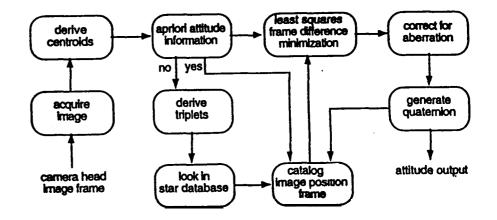
The Advanced Stellar Compass Innovation

Feature	1st Generation Conventional Star Trackers	2nd Generation Advanced Stellar Compass		
Stars Tracked	2t06	25 to 200		
Acquisition	Individual star images	Solves Lost-in-Space problem		
Autonomy	External	Internal		
Primary Output	Star Centroids (Internal Ref.)	Quaternion (Celestial Sphere Attitude Ref.)		
Sensor	Custom CCD (High cost)	Camcorder CCD (Low cost)		
Optics Speed	f /1.7	f/ 0.7		
Mounting/ Boresight Accuracy	20 to 50 arcsec	~1 arcsec		
Mounting	Planar	Kinematic/Ball		
Unit Cost	±\$750k	~\$150k		



ASC Operating Principles

- Fully Autonomous
- Initial attitude acquisition
 - Direction cosine matrix/ quatemion
 - Star triad angle matching
 - 2,20O star database



- Tracking
 - Typically, 65 stars per frame
 - 10,301 star catalog in right ascension and declination
 - Analog like attitude noise behavior as a function of number of stars tracked
 - Full coverage over whole sky
 - Smooth performance without significant attitude jumps

Camera Head Unit

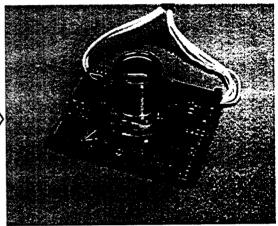
Optics

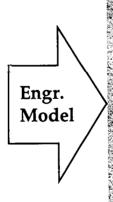
- Custom design and fabrication by Copenhagen Optical Co.
- Refractive 7 element double Gauss
 Spectral range 400 to 760 nm
- Field of view 16 x 22°
 Focal length, 16 mm
 Aperture, 20 mm
 Mass, 80 g
- Optimized for star tracking with
 50 μm point spread function

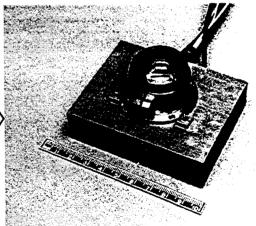
Detector

- Sony CDX 039 AL
- 582 x 752 pixels
- Interline w/microlens for high sensitivity/fill factor
- Pixel FOV, 100x 100 arcseconds
- $-\cos t < 500



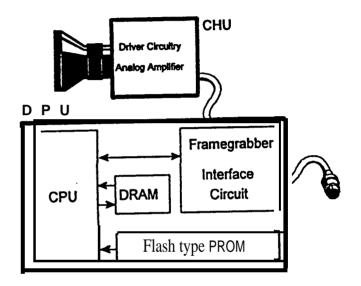


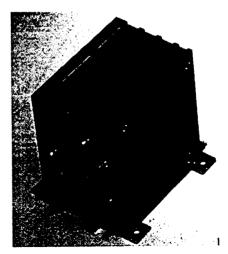




Data Processing Unit

- Processor, radiation resistant, 100MHz, 80486
- DRAM, 4 mbytes
- Flash RAM, 4 mbytes
- Update Rate, 1 Hz, adjustable
- Operating temperature, 22° C
- Mass, 1.5 kg (Ørsted), 0.8 kg (Astrid II)
- Power, 5 W
- Size, $10 \times 10 \times 9 \text{ cm (Astrid II)}$





JPL Components of Accuracy/Error

- Major categories of errors
 - NEA
 - Dynamic
 - Boresight
- NEA
 - Static
 - High frequency terms
 - Principal components: Photon and system noise
- Relative Accuracy composed of NEA plus dynamic terms of:
 - Star catalog error
 - Abberation correction error
 - Lens chroma error
 - CCD pixel-to-pixel variations
 - Centroiding residual
 - Close object fusing
 - False object lockTime stamp uncertainty

JPLComponents of Accuracy/Error (cont.)

- Total error composed of relative accuracy plus long-term boresight error term of:
 - Calibration error
 - Launch effects
 - Mounting uncertainties
 - Thermal/mechanical terms

ASC-O Error Budget

- ASC-O Relative accuracy error budget
 - Earth orbiting
 - Average values
 - Major terms from measurements
 - Minor terms estimated
- Catalog effects
 - HIPPARCOS measurements assumed
 - ASC values weighted sum when affected by close objects
- Beginning of life values, RMS, single axis
 - NEA 0.55 arcsec
 - Relative accuracy 1.42 arcsec
- End of life values, including proton flux transient hits, RMS, single axis
 - NEA 1.52 arsec
 - Relative accuracy 2.01 arcsec

	NEA (RMS)	Relative precision (RMS)
Star catalogue error	0.002"	0.04"
Aberration Corrector, residual error		
Lens. Thermal and mechanical effects		•
Lens. Residual Geometric Distortion	0.4"	1 .0
Lens, Residual Chromatic Distortion	0.08"	0.1"
CCD Thermal and mechanical effects		
CCD pixel to pixel variations	0.000"	0.02"
CCD residual Dark-Current noise	0.01"	0.01"
CCD. Photon noise	0.05"	0.05"
CCD, Charge transfer Efficiency (CTE)	0.000"	0.01"
CCD, Integral non-linarity	0.000	0.05-
Amplifier noise	0.06	006"
AID noise	0.1"	0.1"
Algorithmic. Centroiding residual	00-\$"	0.04"
Algorithmic, Close object Fusing residual	0.25"	0.9"
Algorithmic. false object lock	0.25"	0.4"
Algorithmic, LSF residual	0.01"	0.01"
Time/stamp. uncertainty	0.000"	0.1"
Precision, BOL	0.55"	1.42"
Radiation, Proton noise (transient/flare)	1.0"	1.0"
Radiation CTE degradation	1.0"	1 0"
Radiation hot pixels	0.000"	0.000"
Radiation, Lens degradation	*****	V.000
Precision. EOL	1.52"	2 01"



ASC-HP Error Budget

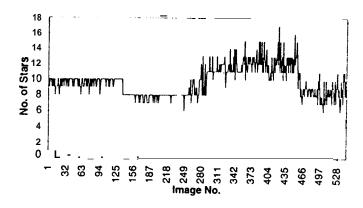
- ASC-HP Relative accuracy error budget
 - Solar orbiting
 - Staring mode NEA
 - Dynamic relative accuracy
 - Major terms based on measurements
 - Minor terms estimated
- Catalog effects as ASC-O
- Relative accuracy values dominated by lens distortion residual and close object fusing—subject to future improvement
- Beginning of life values, RMS, single axis
 - NEA 37 milliarcsec
 - Relative accuracy 0.502 arcsec
- End of life values, RMS, single axis
 - NEA 37 milliarcsec
 - Relative accuracy 0.504 arcsec

	NEA	Precision
	(RMS)	(RMS)
Star catalogue error		0.04"
Aberration Corrector, residual error		
Lens. Thermal and mechanical effects		
Lens, Residual Geometric Distortion		0.330"
Lens, Residual Chromatic Distortion		0.020-
CCD Thermal and mechanical effects		
CCD pixel to pixel variations		0.004"
CCD residual Dark-Current noise	0.003"	0.003"
CCD, Photon noise	0.013"	0.o13-
CCD, Charge transfer Efficiency (CTE)	0.000"	0.002"
CCD, Integral non-linearity	0.003"	0.010
Amplifier noise	0.016"	0.016"
A/D noise	0.016"	0.020-
Algorithmic.Centroiding residual	0.026"	0026"
Algorithmic, Close object Fusing residual		0.450"
Algorithmic. false object lock	0.000	o 0s0'"
Algorithmic, LSF residual		0.002"
Time/stamp, uncertainty	0.000"	0.020"
BOL Value	0.037"	0502-
Radiation CTE degradation		
Radiation hoc pixels (<30 kRad)		0.050*
Radiation. Lens degradation	0.000"	0.000"
EOL Value	0.037"	0.504"

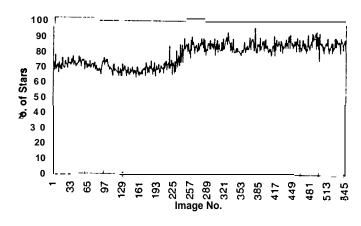
JPL Stars Acquired and Tracked

- Performance dependent on tracking a large number of stars
- Stars acquisition and tracking tested at University of Hawaii, Mauna Kea, June 1996
- Fixed pointing, zenith series with stars drifting at sidereal rate
- 582 data frames taken
- 6 to 17 stars recognized per frame
- 63 to 95 stars tracked per frame

No. of stars recognized in initial attitude acquisition



No. of stars tracked in each image



JPL Key Parameters of ASC Variants

PARAMETERS	Ø(m1)	AII(p)	I(m2)_	HP(p)
Star sensitivity threshold, MI	6.0	4.0	6.0	9.5
Acquisition data base, number of stars Tracking data base, number of stars	2,200 10,301	TBD TBD	2,200 10,301	42,654 231,435
Noise equivalent angle, 1 axis, RMS, arcsec (a)	1.0	2.1	1.5	0.037
Relative accuracy, 1 axis, RMS error, arcsec	1.4	(a)3.0	2.0	0.54
Mass, camera head, kg	0.13	0.20	0.45	<2.0
Mass, processing electronics, kg	1.4	0.80	0.90	1.0
Power consumption, camera head, W	0.5	0.4	0.4	0.4
Power consumption, proc. elec's, W	5.0	5.0	5.0	6.0
Field of view, degrees	16x22	16x22	16x22	3.3x4.5
Update rate, Hz	1	0.5–2	0.5–2	1
Permissible radiation dosage, krad	10	10	200	20

Ø=Ørsted; AII=Astrid II; HP=High Precision; I=Interplanetary a=without image motion smear; ml=measured at Mauna Kea, 6/96; m2=measured at JPL/TMO, 8/96; p=projected